Widely tunable distributed-feedback lasers with chirped gratings

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A quasicontinuous tuning range of 65 nm at 3.2 μm was obtained for continuous wave, single-longitudinal-mode operation at 77 K of an optically pumped distributed-feedback laser with a chirped grating. Interferometric lithography with spherical wavefronts was used to fabricate a large-area chirped grating whose period varied continuously in the direction of the grating lines. Tuning was achieved by translating the optical pump stripe relative to the device to activate regions with different grating periods. Methane absorption spectra, obtained using this tunable distributed-feedback laser, closely match the high-resolution transmission molecular absorption database simulations. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3123813]

The mid-IR (3–5 μm) atmospheric transmission window is important for spectroscopic applications because it contains many fundamental molecular absorption lines including the C–H stretch at $\sim$3.3 μm. Many spectroscopic applications require a continuous wave (cw), single-longitudinal-mode (SLM), widely tunable, high-power laser source. Recently, we have reported an optically pumped type-II distributed feedback (DFB) laser with high output power (>560 mW/facet) in a cw SLM operation at 3.64 μm.[1] However, the thermal tuning range of that device was only $\sim$6.8 nm limited by the laser performance at higher temperatures. The thermal tuning ranges of intersubband quantum cascade[2] and interband cascade[3] DFB lasers are generally limited to <20 nm (0.5% $\Delta\lambda/\lambda$). Tuning range enhancing technologies such as superstructure gratings DFB (Ref. 4) and selectable DFB arrays[5] can extend the tuning range to $\sim$10% $\Delta\lambda/\lambda$. However, both of these technologies require rather complex laser structures and tuning protocols. In this paper, we report a tuning method using a chirped DFB grating that is easily fabricated using spherical-wavefront interferometric lithography (IL). A quasicontinuous tuning range of 65 nm (2% $\Delta\lambda/\lambda$) was obtained from a 3.5 mm wide chirped-grating DFB laser for cw SLM operation at 3.2 μm. Spectroscopic experiments using the tunable DFB laser as a light source yield methane absorption spectra that closely match high-resolution transmission molecular absorption (HITRAN) simulations.

The type-II laser device was grown by molecular beam epitaxy.[6] It consists of a GaSb:Te substrate (index $n_{sub}=3.82$), a 1.5 μm thick active region ($n_{active}=3.84$) consisting of 14 type-II InAs/InGaSb/InAs W-quantum wells, and a 1.5 μm thick top clad layer ($n_{clad}=3.82$). A 500 nm thick, high-index germanium (Ge) layer ($n_{Ge}=3.99$) was deposited on the top clad to increase the modal confinement in the active region. A 450 nm deep chirped grating was fabricated in the Ge layer using IL and inductive coupled plasma etching, giving a coupling coefficient $\kappa \sim 4$ cm^{-1}.

A planoconvex lens (focal length $f=37.8$ mm) was used in IL to transform the plane wavefronts of the 355 nm laser into spherical wavefronts, as shown in Fig. 1(a). The interference pattern is therefore a series of hyperbolae,[7] [Fig. 1(b)] that provide a chirp of the grating period along the device. The grating was deliberately tilted 6° relative to the facet in order to suppress the Fabry–Perot (FP) modes when the pump stripe is perpendicular to the grating.[1] The wafer was then lapped to a thickness of 150 μm. A 2.5×3.5 mm^2 device was cleaved and indium-soldered (active region up) to a copper heat sink mounted in a 77 K liquid nitrogen dewar. For the device with a cavity length L of 2.5 mm, the coupling strength is estimated to be $\kappa L \sim 1$. The grating period ranges from 425 to 435 nm (3%) in the lateral direction (parallel to the grating), corresponding to a DFB wavelength from 3200 to 3270 nm. There is also a 0.2% period chirp in the longitudinal direction (perpendicular to the grating) between the center and edge of the device. This longitudinal chirp introduces a continuously distributed phase shift in the grating.[8]

A 1908 nm cw fiber laser source was used to illuminate an 80 μm wide stripe across the device, providing both laser gain and lateral mode guiding. The device worked well only when the pump stripe was oriented perpendicular to the facet, because the grating, with a small κL, did not provide sufficient optical feedback without the help of facet reflection. In this configuration, there is a 6° tilt between the pump stripe and the grating, similar to a tilted-ridge DFB laser.[9] Due to the facet reflection, there remains an influence of the

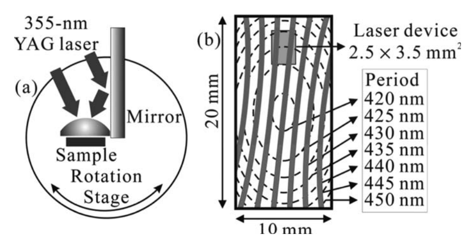

FIG. 1. (a) The spherical wavefront IL arrangement for chirped gratings; and (b) the 6° tilted hyperbolic chirped grating (solid lines) and the elliptic period contour (dashed lines). The position of the laser material during the exposure is indicated.

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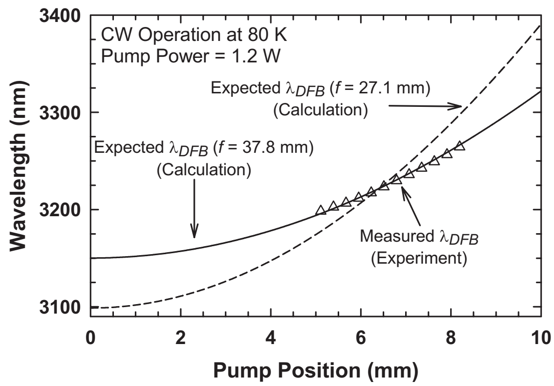

FIG. 2. Expected chirped-grating DFB tuning curves based on the focal length f of the lens used for the IL. Dashed line for $f=27.1$ mm and solid line for $f=37.8$ mm. Triangles represent the measured wavelengths.

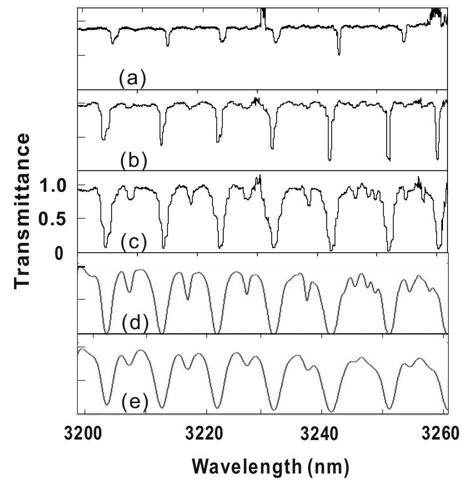

FIG. 3. [(a)–(c)] Experimentally obtained transmittance spectra of methane at 20, 100, and 400 torr, respectively; [(d) and (e)] HITRAN simulations of methane spectra at 400 torr for a laser linewidth of 0.1 and 1 nm, respectively.

FP modes on the laser spectrum. At lower pump powers, (up to about four times threshold) the laser exhibits SLM emission, with the peak of the DFB mode always located at the wavelength of the nearest FP mode. At higher pump powers, there is significant energy contained in FP modes at the peak of the gain spectrum that are independent of the grating.

The DFB laser emission was directed into a 1/2-m monochromator with a spectral resolution of 0.2 nm, and recorded by a 77 K InSb photodiode with standard signal processing electronics. The spectra of the laser were recorded as the device was translated relative to a fixed pump stripe. A 65 nm tuning range was achieved at a fixed pump power of 1.2 W ($1.7\times$threshold) where the SLM wavelength is controlled by the grating (Fig. 2). A tuning rate of 18.6 nm/mm is obtained, as indicated in Fig. 2. This was controlled by the focal length of the lens used for the IL. A gear-reduced stepper motor, with a position step corresponding to a tuning of 0.002 nm was used to adjust the laser position relative to a fixed pump stripe (and collection optics). The laser linewidth was ~0.6 nm and the output power was ~30 mW. The potential tuning range, limited by the grating fabrication, for a 10-mm-long device, is ~170 nm using a 37.8 mm focus lens in IL, and ~300 nm using a 27.1 mm focus lens in IL. At a fixed pump stripe position near the center of the device, the maximum cw output power was ~560 mW/facet (including the nongrating-related FP emission peaks) while the maximum cw SLM output power was ~200 mW/facet.

Spectroscopic measurements of unbuffered methane (CH_4) gas were conducted using the chirped-grating DFB laser as a tunable light source. A 10 cm gas cell was placed in the path of the DFB laser beam. The transmittance spectra of methane was obtained by recording the signal from the InSb photodiode after the gas cell, divided by the signal from the InSb photodiode before the gas cell, as the laser wavelength was tuned in 0.02 nm steps by mechanical translation of the laser relative to the fixed pump stripe. The transmittance spectra of methane at different pressures are shown in Figs. 3(a)–3(c). A comparison between the experimentally obtained methane transmittance spectrum at 400 torr [Fig. 3(c)] and HITRAN simulations using different laser linewidths [Figs. 3(d) and 3(e)] suggests a DFB laser linewidth between 0.1 and 1 nm, in agreement with the measured linewidth of ~0.6 nm. Careful examination of the methane transmittance spectrum reveals steplike features with a width of 0.56 nm, the same as the FP cavity mode interval for the 2.5-mm-long cavity, showing that the peak of the laser spectrum hops among FP modes during tuning. The wavelength tuning is therefore classified as quasicontinuous. Since the laser linewidth is comparable to the FP spacing, continuous frequency coverage is obtained. The experimental linewidth is large in comparison with other DFB lasers as a result of the absence of transverse structural mode control (e.g., a ridge), the wide pump stripe, and the low confinement associated with the large-optical cavity design. The tradeoff for this weak transverse/lateral confinement is higher SLM output power and suppression of filamentation, but with a larger linewidth. The experimental linewidth is quite suitable for atmospheric-pressure molecular spectroscopy.

In summary, we have demonstrated cw SLM operation of an optically pumped, type-II, chirped-grating laser with a 65 nm quasicontinuous tuning range at 3.2 μm. Methane spectroscopy experiments using this tunable laser closely match HITRAN simulations. If a 27.1 mm focus lens had been used in IL, the period chirp of a 10-mm-wide device would have been ~40 nm, corresponding to a potential tuning range of ~300 nm at 3.2 μm ($\Delta\lambda\lambda \sim 10\%$). A two-partition optically pumped type-II laser incorporating two different sets of quantum wells has been recently developed.[10] The same design can be used in a nonpartitioned device to provide an extended gain bandwidth (~500 nm) to support the broad tuning range of the chirped DFB design.

Two directions for improving the tuning are immediately evident. A longer device would further reduce the FP mode spacing, which is already comparable to atmospheric-pressure-broadened molecular linewidths, insuring that all lines are captured. Alternatively, the mode hopping among FP modes during tuning can be avoided by orienting the pump stripe perpendicular to the grating, provided that a larger κL can be obtained. Work is underway to investigate higher confinement epitaxial designs that should provide continuous and smoothly tunable frequency coverage.

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